



Three Decades of Precision Orbit Determination and its Vital Role to Oceanography

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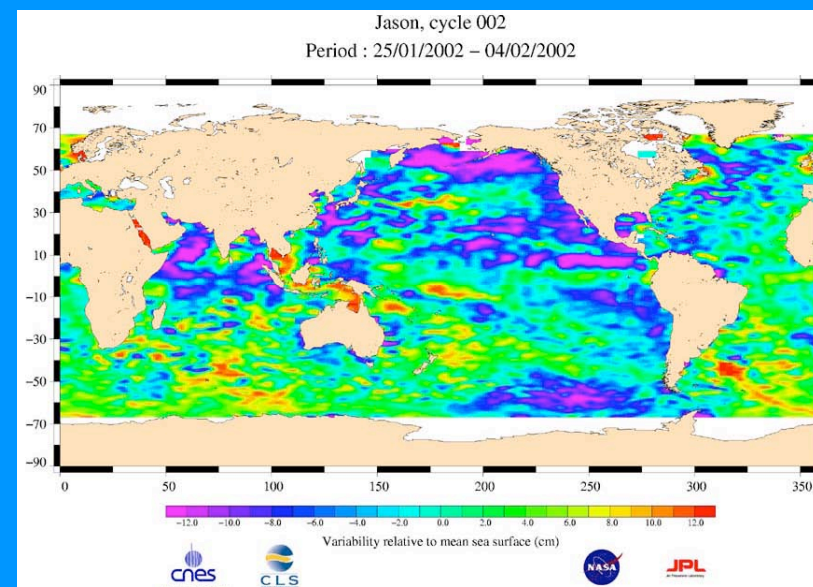
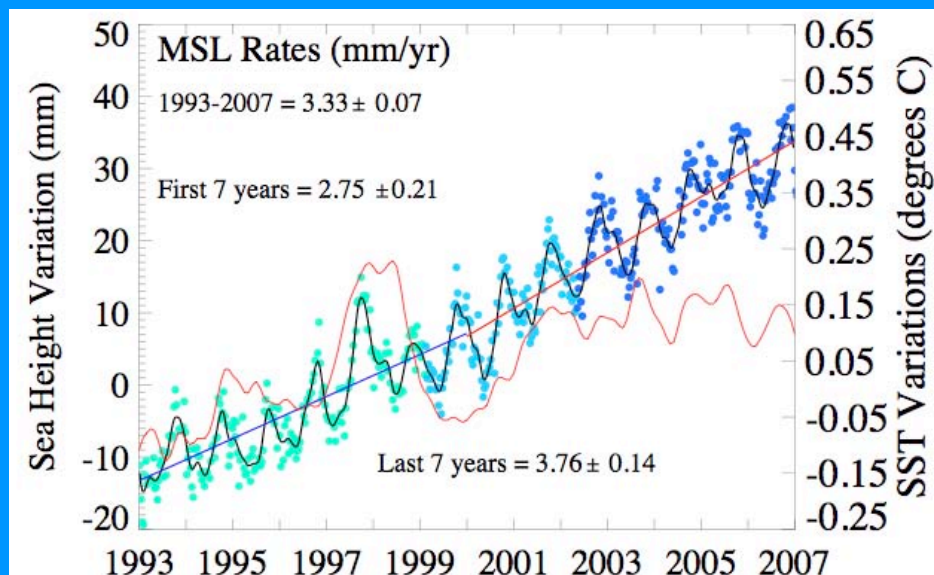
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From the launch of the first spaceborne altimeters, Precision Orbit Determination (POD) has been driven by the science goals of the geodetic altimeter missions...



The accurate knowledge of the spacecraft ephemeris in an accurate common reference frame is essential to the successful science derived from radar altimetry, particularly for global circulation and MSL studies...

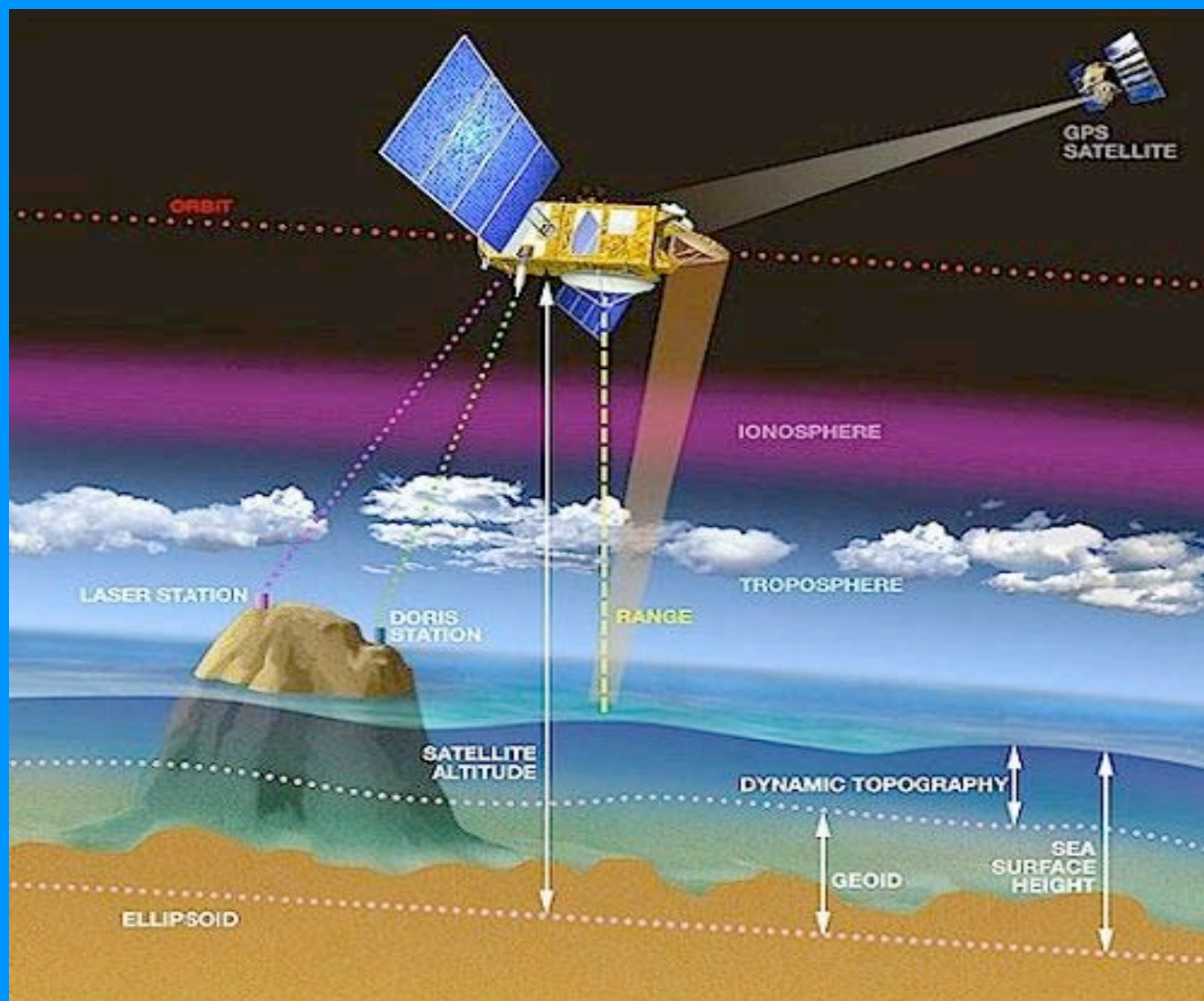


Meeting mission POD accuracy requirements has depended on advances in each of the following areas

- 1) Accurately modelling the forces acting on the satellite... Force Modelling***
- 2) Accuracy and consistency of the reference frame as realized through the ground and space based tracking network ... Reference Frame***
- 3) Observing the satellite motion with high temporal sampling and accuracy ... Tracking Technology and Measurement Modelling.***



POD Schematic



OSTM SWT, June 19, 2008

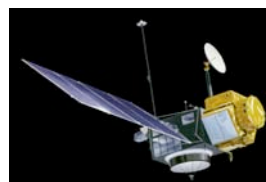


Orbit Determination



Onboard Tracking Systems

LRR
DORIS
GPS



Atmospheric Modeling

Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

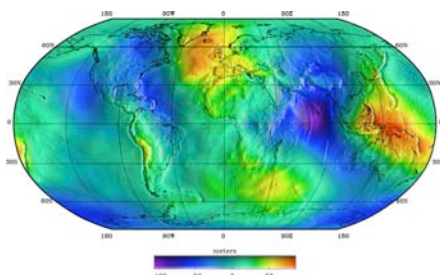
Surface Forces

Modeling
S/C Attitude



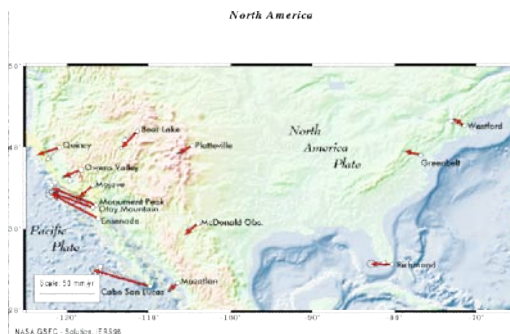
Orbit Determination

Force Modeling
Reference Frame
Tracking Technology



Geophysical Models

Gravity Models
Tide Models
Time Variable Gravity



Reference Frame

International Terrestrial Reference Frame
Horizontal plate and vertical site motion
Geocenter motion
Polar Motion and Earth Orientation



The Geodetic Networks are the Key to Altimeter Satellite Mission Success



SLR, Maui



SLR, Graz, Austria

Satellite Laser Ranging (SLR)





DORIS (Ground Network)



Rothera



Thule



*International
DORIS
Service*

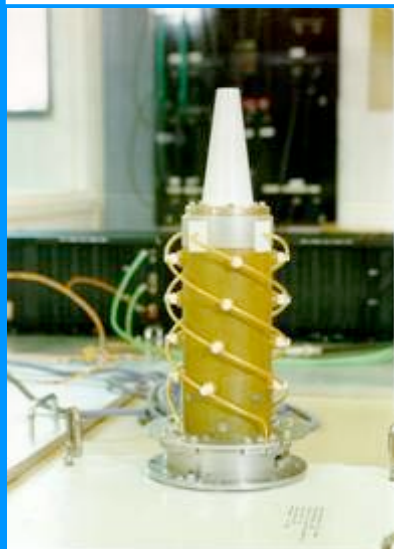


DORIS (Satellite Receivers)

(Table from Jayles et al. 2006)



DORIS antenna



2 kg
h 420 x ϕ 160
(mm)

1st generation (WBUT = 18 kg) SPOT2, SPOT3, TOPEX-Poseidon (*), SPOT4 1 channel	2nd generation (WBUT = 5.5 kg) ENVISAT (*) 2 channels	2nd generation miniaturised (WBUT = 3 kg) Jason-1 (*), SPOT5 2 channels
Intermediate DGXX (WBUT = 3 kg) CryoSat (*) 2 channels	Full DGXX generation (WBUT = 1.15 kg) Jason-2, Pléiades, AltiKa 2 x 7 channels twinned (redundant) in one box including USOs and automated antenna switching	

1st. Generation receivers can track one beacon at a time; 2nd generation can track two beacons; Jason-2 & later can track up to seven beacons.

(Therefore much more tracking data is available from ENVISAT & SPOT5 & Jason-1 than on SPOT2 & TOPEX/Poseidon).





GPS Tracking System for OSTM

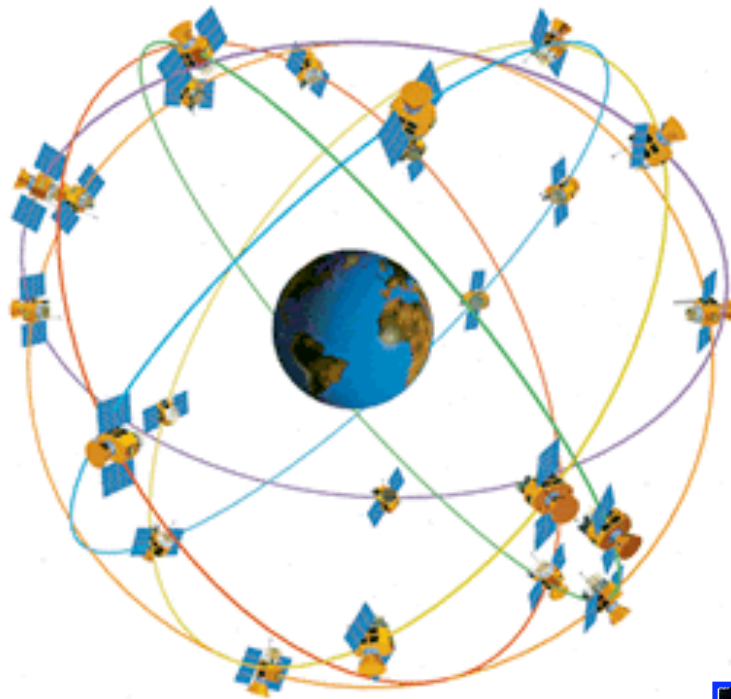


International GNSS Service

Formerly the International GPS Service



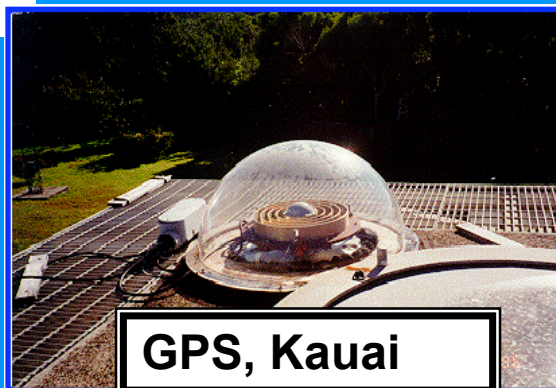
GPS Satellite Constellation



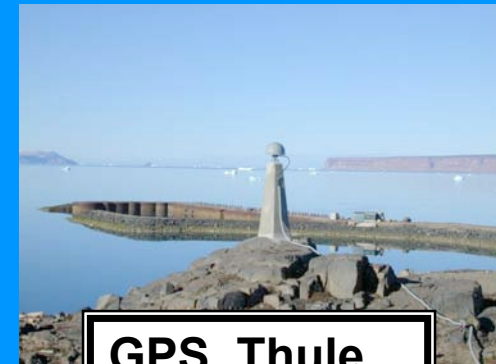
JASON GPS Receiver



Examples: Ground Receivers



GPS, Kauai



GPS, Thule

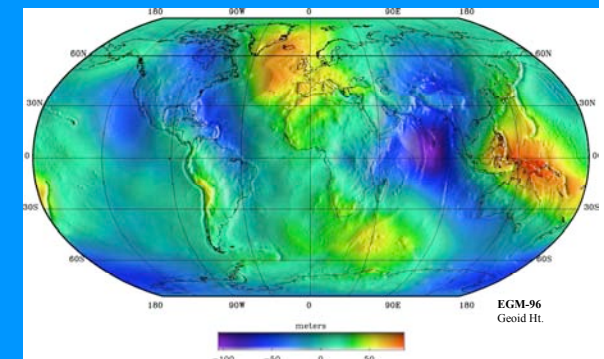


Errors in Models of the Earth's Gravity Field were the largest source of orbit error for altimeter missions ... Until the launch of TOPEX/Poseidon



Model	Radial Calibration (cm)	SLR rms fit (cm)
GEM-L2: 1982	65.4	105.9
GEM-T1: 1988	25.0	31.4
GEM-T2: 1990	10.2	17.8
JGM-1S: 1991	6.0	7.7
JGM-2S: 1992	2.9	4.0
JGM-2: 1992	2.2	3.8
JGM-3: 1995	0.9	3.2
EGM-96 1997	0.8	2.8

**GEML2: 20x20
JGM1-3: 70x70**





Significant advancement in POD accuracy achieved for GEOS-3 (1979) due to gravity field modeling improvement...

Armed with a suite of tracking technologies, including Satellite Laser Ranging (SLR), GEOS-3 tracking data significantly advanced the gravity field model and orbit accuracy (Lerch et al. 1979):

- **GEM-9 and 10 complete to degree and order 20**
- **GEOS-3 radial orbit accuracy improvement from ~500 cm to ~130 cm**

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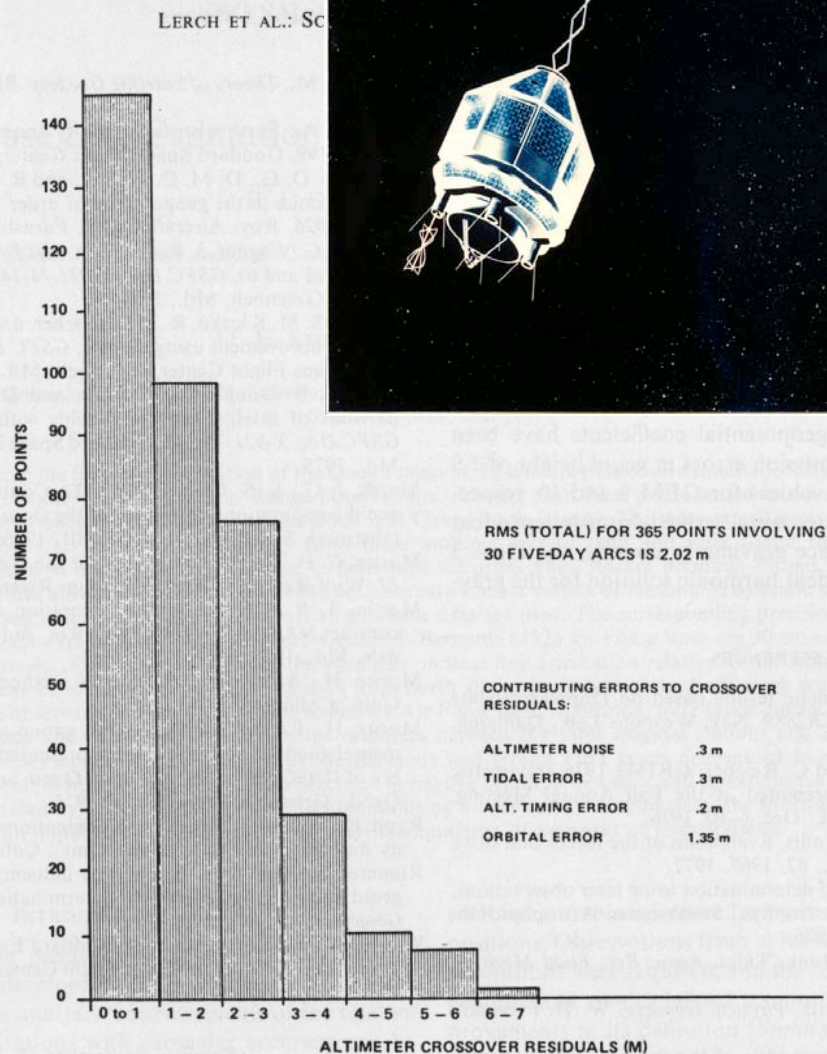


Fig. 11. Histogram of GEM 10 altimeter crossover residual differences.

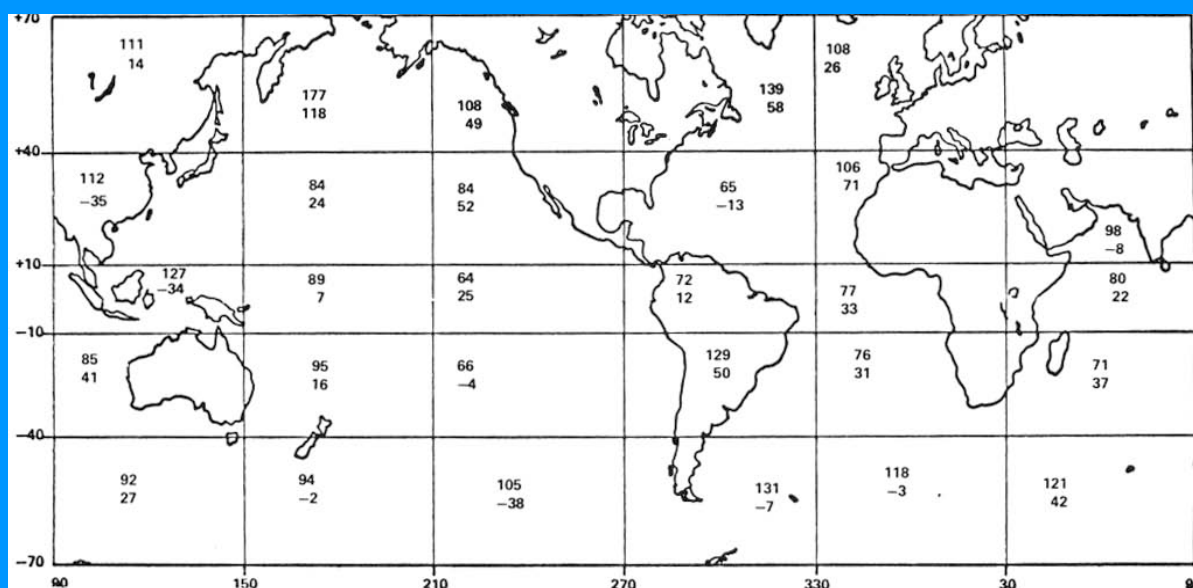
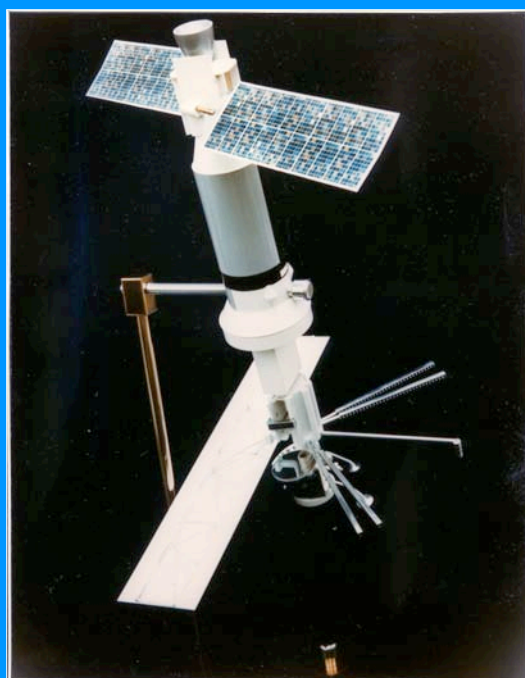


SEASAT (1982) orbit accuracy improvement gained through tailored geopotential model...



Combining SEASAT SLR and USB tracking data along with SEASAT altimeter data with the GEOS-3 based GEM-10 normals produced a SEASAT tailored gravity field, PGS-S4 (Lerch et al. 1982) ...

- PGS-S4 complete to degree and order 36.***
- SEASAT radial orbit accuracy improvement from ~400 cm to 70 cm.***



Altimeter Xover RMS = 110 cm RMS
MEAN
UNITS ARE CM.

Lerch et al. 1982

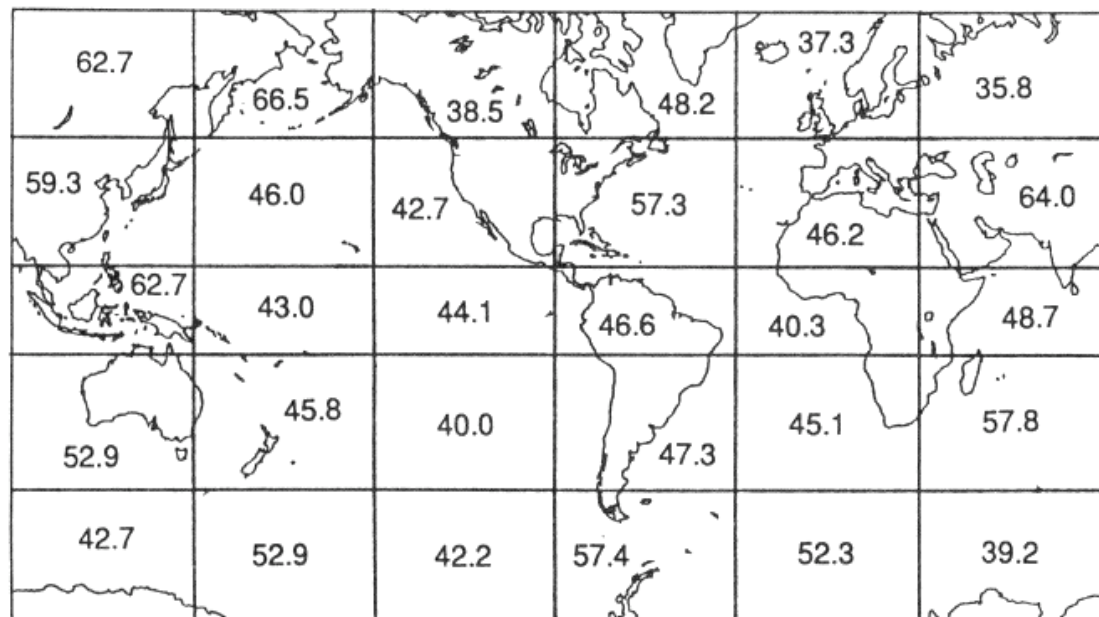


GEOSAT, another leap forward in gravity field modeling and orbit accuracy...



GEM-T2 gravity model advancement including 80-days of GEOSAT ERM TRANET doppler tracking data (Marsh et al. 1989)

- ***GEM-T2 complete to degree and order 36 with selected terms to 50x50***
- ***Radial orbit accuracy ~35 cm (Haines et al. 1990)***

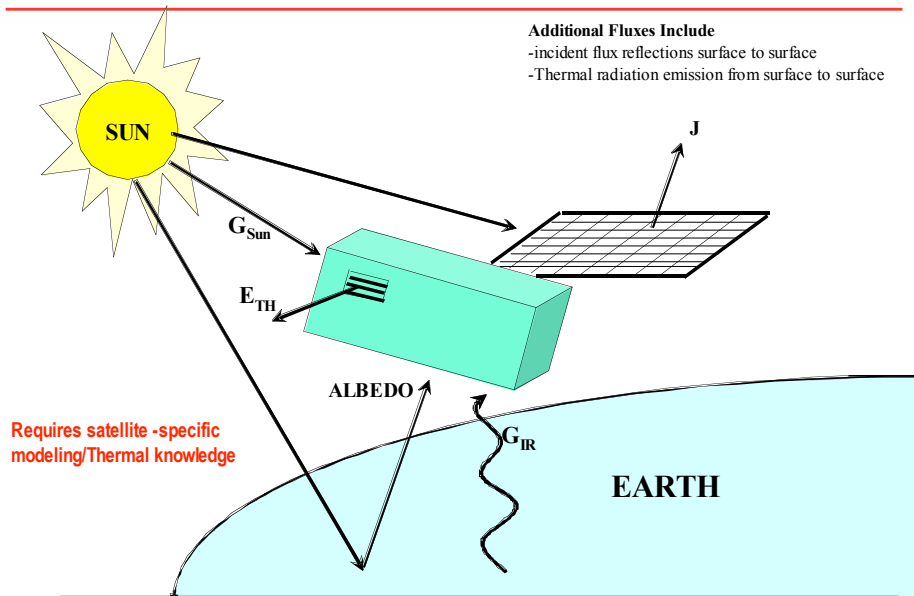




Radiation Pressure Modelling is the largest source of orbit error after gravity model error



Radiative Fluxes



Micromodel

- (Antreasian, 1992; Antreasian & Rosborough, 1992)

Box-Wing model

- (Marshall & Luthcke, 1994)

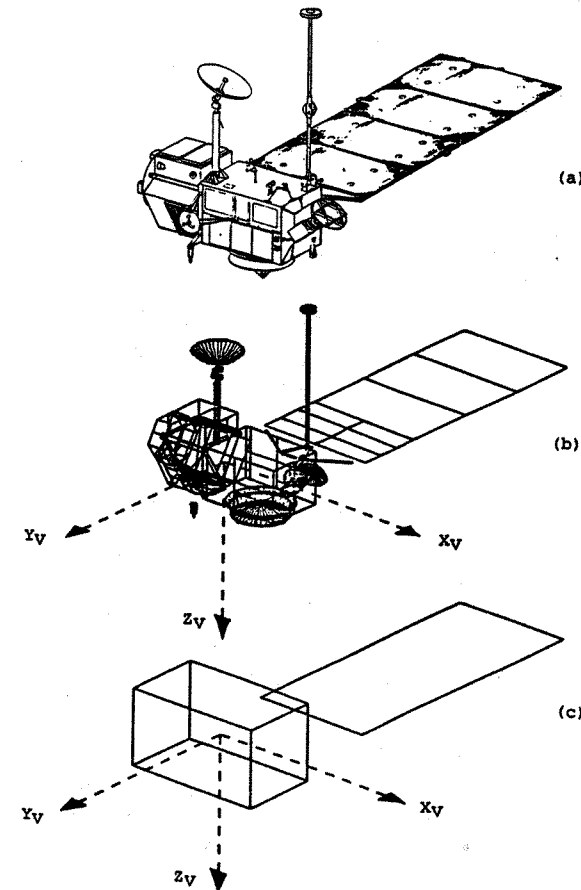


Figure 1. (a) The TOPEX/Poseidon Spacecraft, (b) Micro-Model Approximation, (c) Macro-Model Approximation



TOPEX/POSEIDON (1992)...A giant leap forward in orbit accuracy 2.5 cm orbit accuracy achieved early in the mission (c.f. Marshall et al., 1995)



SIGNIFICANT ADVANCEMENTS WERE DUE TO:

Force modelling improvements:

- **Gravity: JGM-2 (Nerem et al. 1993) JGM-3 (Tapley et al. 1994)**
- **Tide model (Ray et al. 1994)**
- **Improvements in the reduction of surface forces errors:**
 - **Box-wing model (Marshall and Luthcke, 1994)**
 - **Reduced dynamic solution from GPS (Bertiger et al., 1994)**

Advanced tracking technology: SLR, DORIS, GPS, (TDRSS)

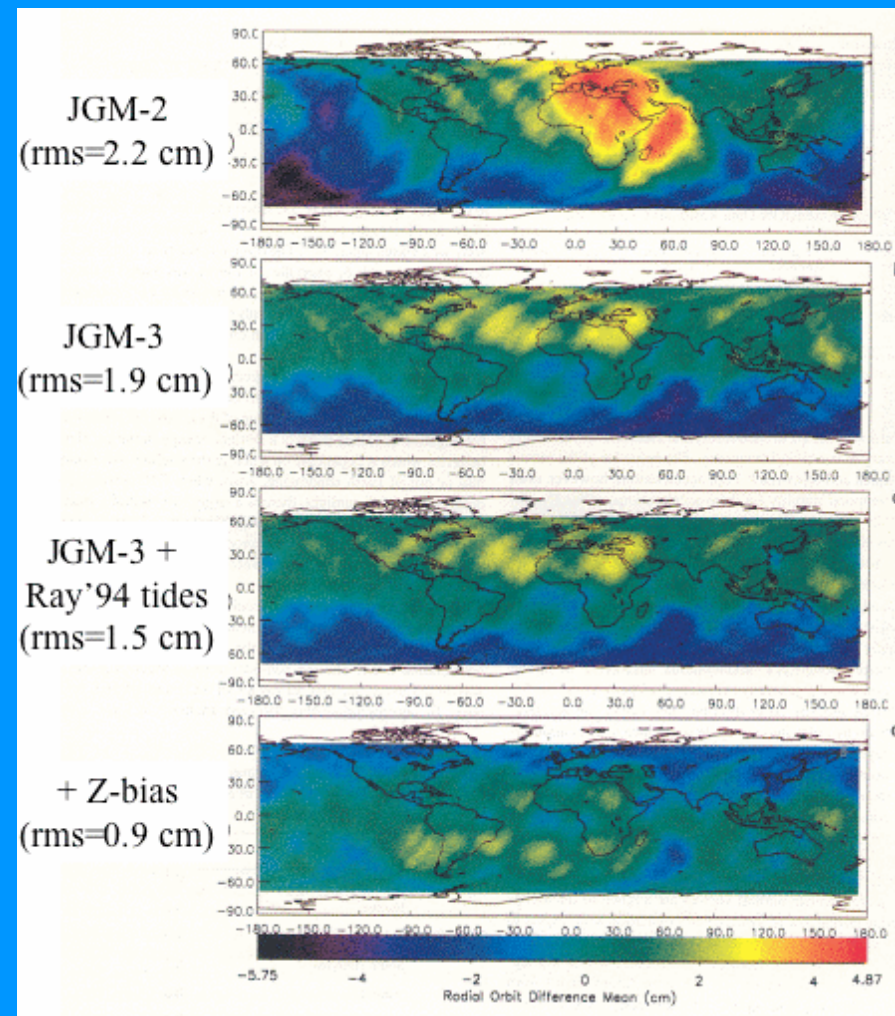
- **GPS and DORIS near-continuous orbit observability is a significant advancement**
- **Ability to characterize orbit error through the comparison of high accuracy orbits determined from independent data (SLR/DORIS vs. GPS)**

Tracking network, reference frame and measurement modeling improvements

Diverse and cooperative POD Team: NASA GSFC, CNES, JPL, UT/CSR, CU, ... with contributions by many others e.g.. The Ohio State University.



Intercomparison of Independent Orbits Produced by SLR/DORIS & GPS (Reduced Dynamic) allows insights into model and geodetic technique error And helps to validate improvements



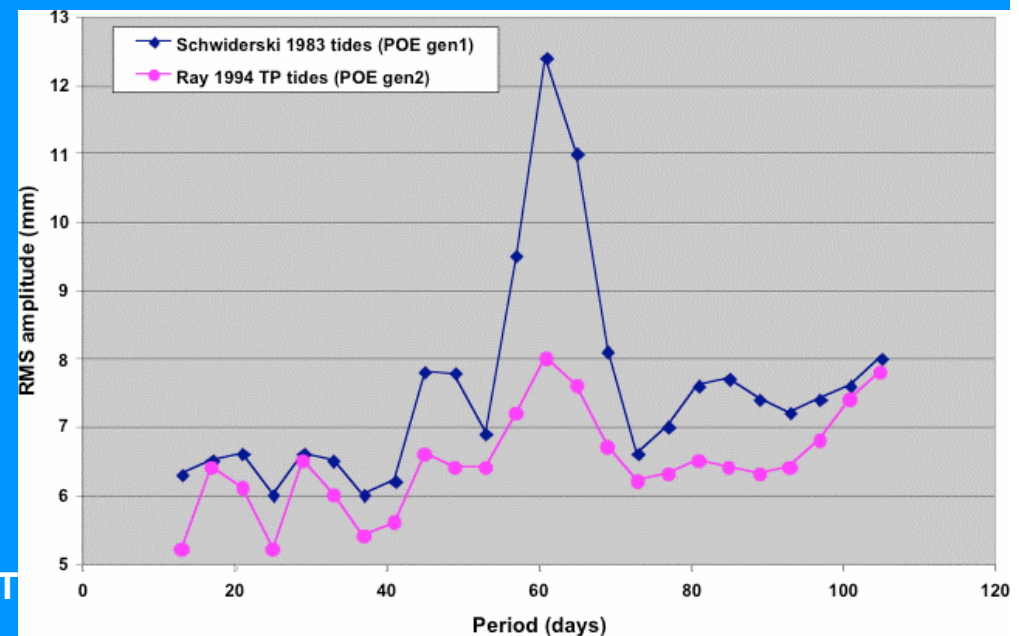
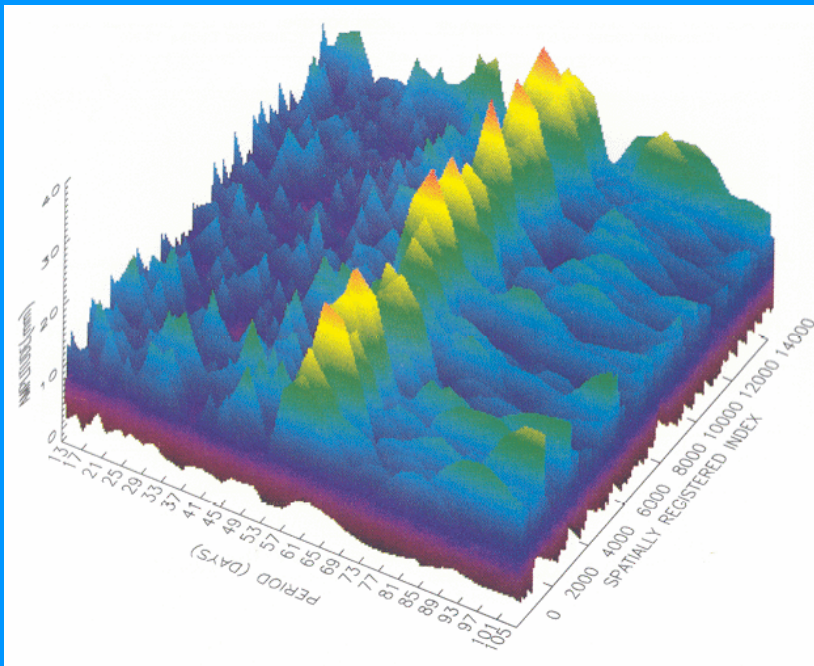


Intercomparison of SLR/DORIS (dynamic) & GPS (reduced-dynamic) orbits revealed Tide model induced orbit error



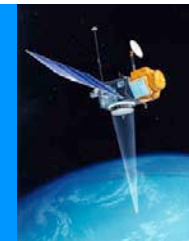
**A priori (Schwiderski) Tide
model produced orbit error at
the M2 alias period (~60 days)
for T/P**

**Tide model improvement
using TOPEX altimeter data**





Jason-1 (2001): The 1-cm orbit ...



- ***1 cm radial orbit accuracy demonstrated (Luthcke et al. 2003, Haines et al. 2004, Choi et al., 2004).***
- ***Retained T/P's diverse and cooperative POD Team: CNES, JPL, NASA GSFC, UT/CSR.***
- ***Applied Upgraded tracking technology: GPS, SLR, DORIS (Especially JPL GPS BlackJack codeless receiver).***
- ***Improved tracking network positions and measurement modelling (e.g. GPS antenna phase center modeling)***
- ***Improved application of the reduced dynamic solutions in GPS, GPS+SLR and even SLR+DORIS based solutions***
- ***The challenge is to assess and characterize the remaining orbit errors***
- ***Necessary to exploit all available tracking data in various combination solutions***



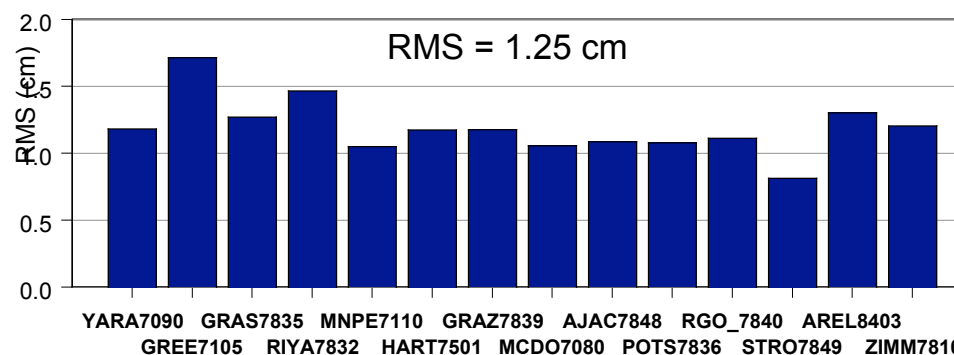
Jason GPS Reduced Dynamic POD Achieved the 1-cm radial orbit accuracy goal...



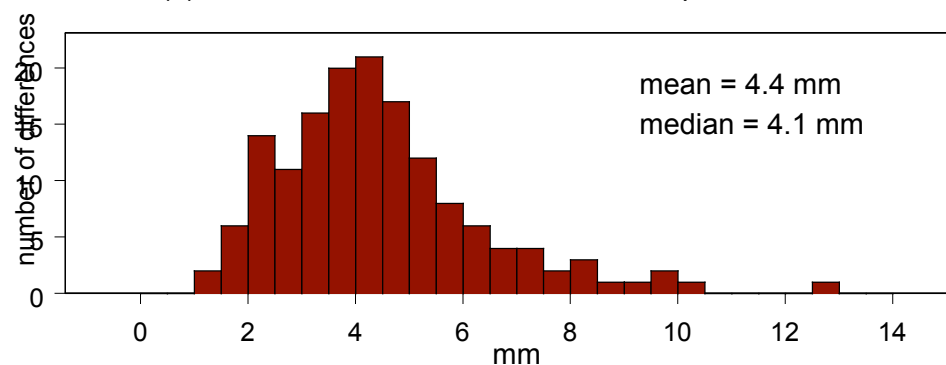
Independent high elevation SLR performance demonstrated the 1 cm radial orbit accuracy (Luthcke et al. 2003).

Other error sources are included beyond radial orbit error.

(a) GPS RD Solution High Elevation Independent SLR Fit



(b) GPS RD Solution Radial Orbit Overlap Performance

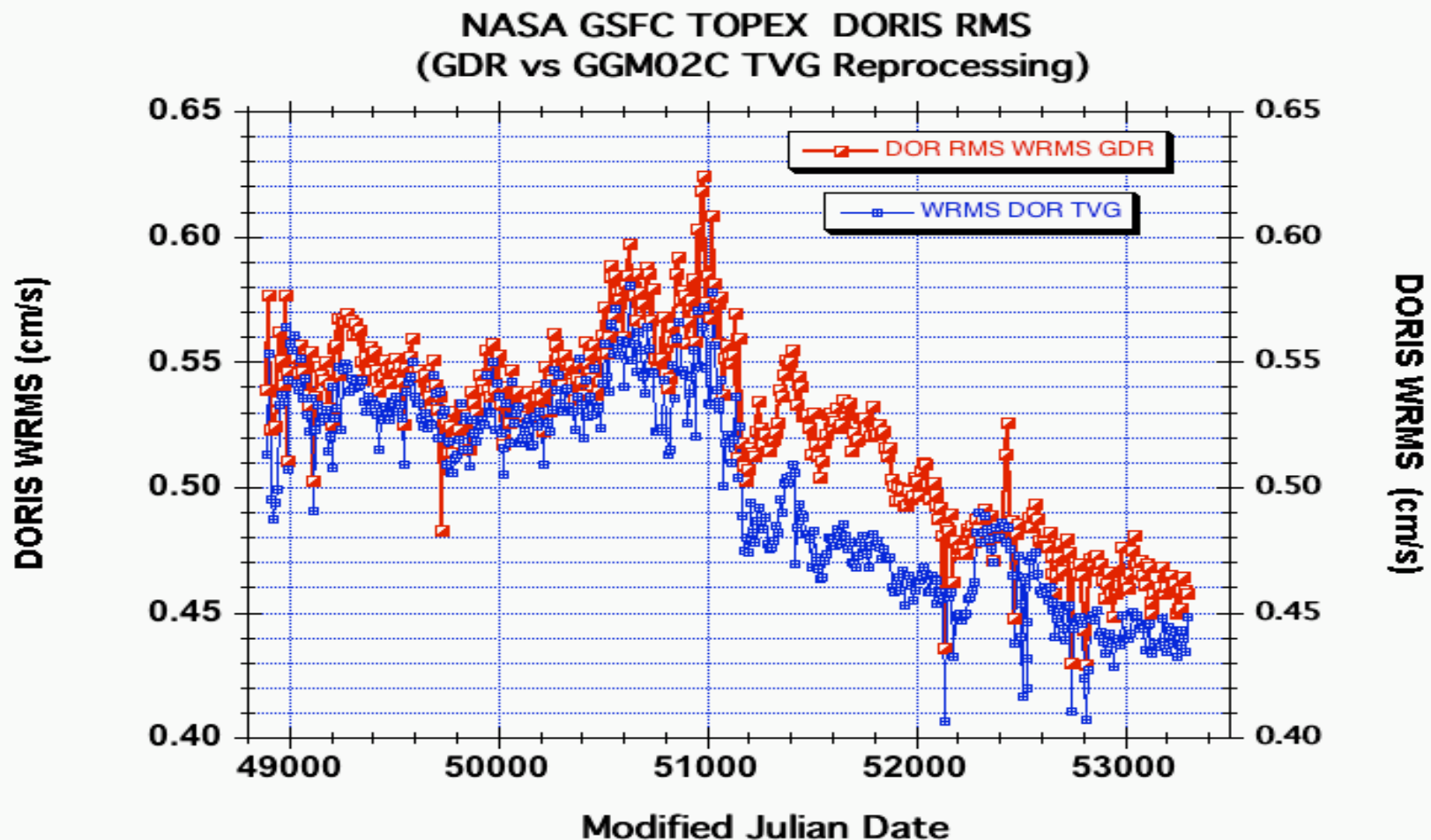




Synopsis of Some Recent Improvements (1) ... Tracking System & Model Improvements (e.g.)

DORIS Evolution from TOPEX re-analysis

(Fagard, H., *J. Geodesy*, 2006, Description of system improvements)

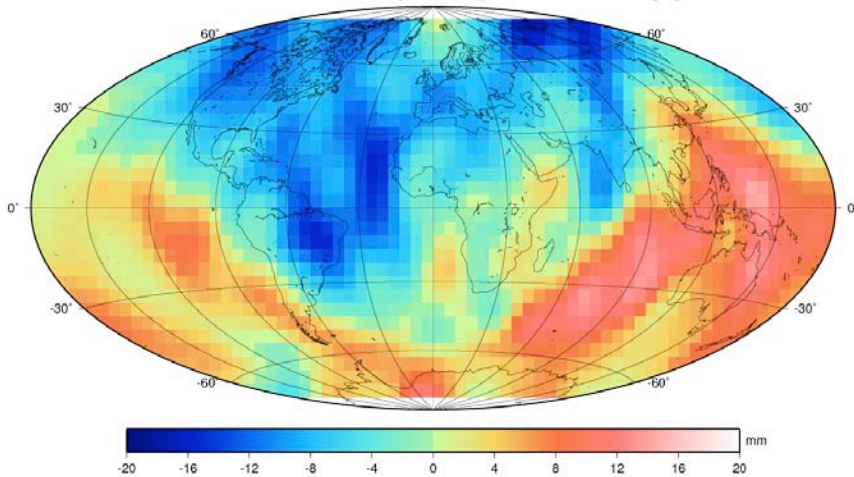




Synopsis of Recent Improvements ... (2)

Improved gravity modelling using products from the GRACE mission

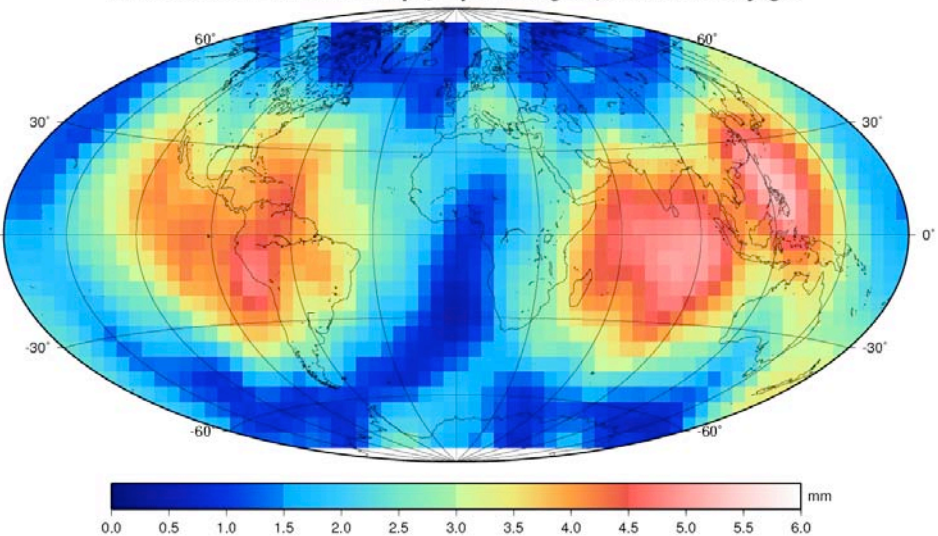
TP Mean Radial Diff.(Sep.92-Aug.02); itr2005.only-gdr



**Geographically
correlated error
removed
(GGM02C vs. JGM3)**

**Model Time-Variable Gravity
due to the Atmosphere &
Land Hydrology**

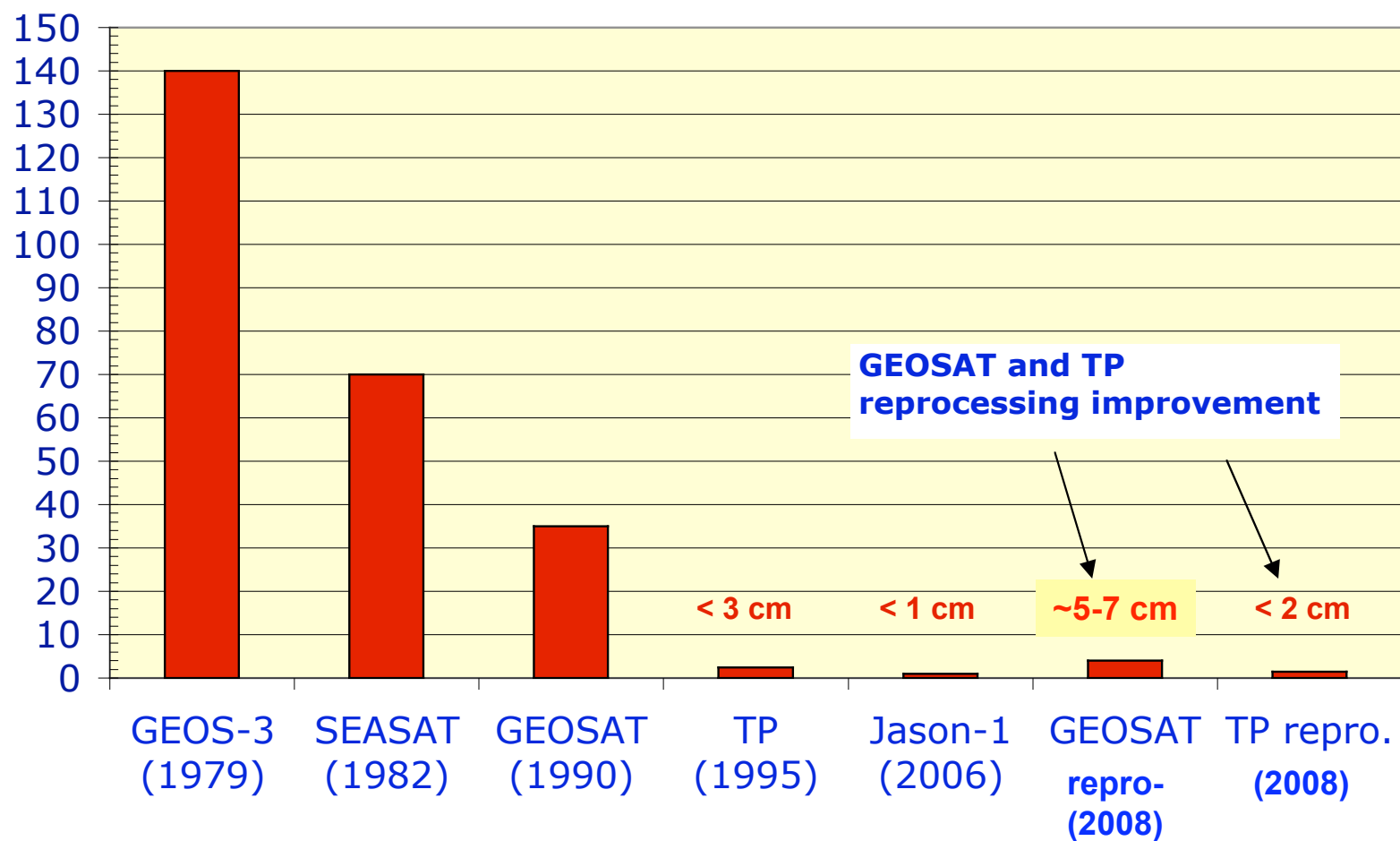
TP Radial Diff. Annual Amp.(Sep.92-Aug.02); itr2005.only-gdr



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Radial Orbit Accuracy Achievement



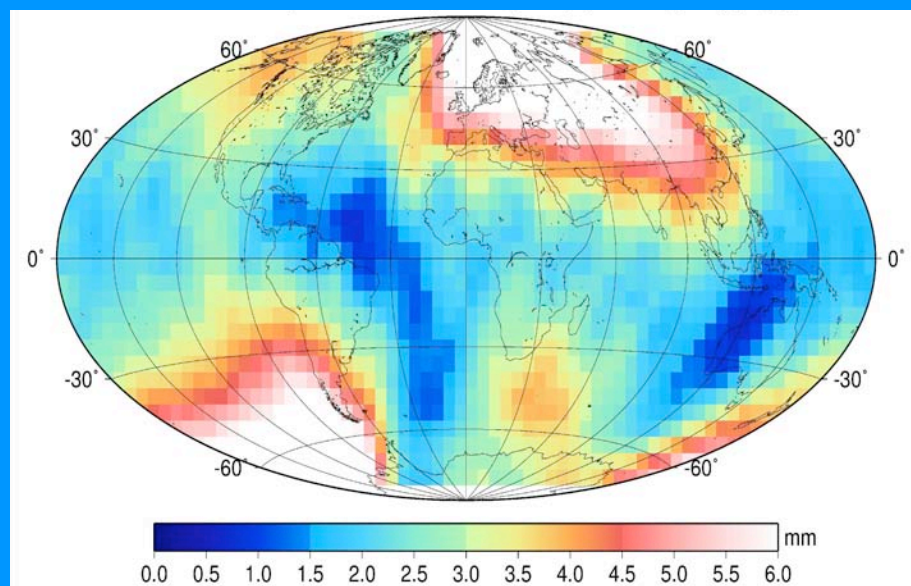


Continued Challenges



Radiation Pressure Modelling:

e.g., SLR/DORIS ($C_R=1$) – JPL GPS6b orbits, 120-day amplitude for Jason-1



1. Providing a consistent orbit time series for altimeter data over 16+ years, spanning three missions, and four altimeters - to better resolve interdecadal signals & MSL change.
2. Radiation Modelling Improvements.
3. Reference Frame Stability.
4. Measurement model improvements for SLR, GPS & DORIS.
5. Geocenter.
6. Deployment of Next Generation Geodetic Stations (SLR, GPS).